Theoretical Issues in the Tevatron Era [1]

Jonathan L. Rosner

Enrico Fermi Institute and Department of Physics
University of Chicago, Chicago, IL 60637 USA

Abstract. The Fermilab Tevatron's operation for fixed-target physics from its start in 1983 until the end of fixed-target running in 2000 was marked by extraordinary productivity and variety. Some of the changing theoretical issues associated with this program are reviewed.

I INTRODUCTION

The Fermilab Tevatron was constructed with several aims in mind. (1) It would permit the storage of counter-rotating beams of protons and antiprotons at beam energies of up to 1 TeV, allowing for collisions at center-of-mass energies approaching 2 TeV. (2) It would demonstrate the first large-scale use of superconducting technology. (3) It would allow the Fermilab energy for fixed-target programs, which had typically been 400 GeV, to be doubled to 800 GeV, and would permit a saving of electrical power. In this last context the Tevatron project was known as the "Doubler/Saver." The present article is devoted to theoretical issues accompanying the Fermilab fixed-target Tevatron program.

Table 1 outlines some topics and how they evolved during the 17 years of Tevatron fixed-target operation, from its inception in 1983 until the end of fixed-target running in 2000. In many cases, theoretical questions have been totally transformed by the advent of precision measurements at the Tevatron and elsewhere. In others, new discoveries have raised as many questions as they set out to answer.

In 1983 the W and Z had just been observed, while we had only a hazy idea of where to look for the top quark, and the tau neutrino was anticipated but not yet seen. Now, with precise measurements of W and Z masses and couplings, and a top quark mass known to a better fractional accuracy than that of any other quark, we can begin to anticipate the Higgs boson mass. For a single Higgs in the Standard Model, the best value comes out tantalizingly close to present lower limits [1]. The discovery of the tau neutrino has been reported [2].

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TABLE 1. Evolution of theoretical topics during the Tevatron era.

Topic	1983	2000
Electroweak symmetry and	W, Z seen	Precision measurements, m_t
	No top	constrain Higgs mass
neutrinos	No ν_τ	Discovery
Weak quark	$\tau(b) \sim 1$ ps!	Precise CKM elements
couplings	$\Sigma^- \to ne^-\bar{\nu}_e$?	Cabibbo confirmed
	τ(charm)?	Hierarchy understood
	Direct CP violation?	$\epsilon'/\epsilon \neq 0$
QCD and	EHLQ $q(x)$	Quark and gluon structure
hadron	Gluons?	functions with error bars
structure	SSC plans	LHC construction under way
	$Q\bar{Q}$ production?	Some progress
	Hyperon polarizations?	Some progress
The unexpected	Magnetic monopoles	Supersymmetry
	Neutral heavy leptons	(but is it really
	Toponium	unexpected?)
	Compositeness	
	1.8 MeV e^+e^- bump	

In 1983, the b quark lifetime had just been shown to lie in the range of 1 ps [3], with the $b \to c$ coupling hence surprisingly small and the $b \to u$ coupling even smaller [4]. The asymmetry in the beta-decay $\Sigma^- \to ne^-\bar{\nu}_e$ [5] disagreed with the prediction [6] of the Cabibbo theory of semileptonic hyperon decays. Charmed particle lifetimes were starting to be mapped out [7] but theoretical understanding of them was primitive [8,9]. CP violation in the neutral kaon system, nearly twenty years after its discovery [10], still could be parametrized by a superweak $\Delta S = 2$ interaction [11] mixing K^0 and $\bar{K}^0$. The proposal [12] that phases in weak couplings of quarks were responsible for this effect was still many years away from being confirmed. Today, we are close to mapping out both magnitudes and phases of weak quark couplings [13]; the beta-decays of Σ^- and other hyperons confirm the Cabibbo theory [14]; the hierarchy of charmed particle lifetimes is at least qualitatively understood [15]; and direct CP violation (as predicted by the Kobayashi-Maskawa theory) has been observed in the form of a difference between the CP-violating ratios $\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)$ and $\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)$ [16,17].

Many problems in QCD and hadron structure were addressed in the Tevatron era. In 1983 the proton structure functions of Eichten, Hinchliffe, Lane, and Quigg [18] helped anticipate physics at supercolliders. The mechanism for quarkonium production was unclear, but a combination of direct QCD effects and electromagnetic cascades from higher levels seemed possible. Hyperons were found to be pro-

duced with polarizations which depended on transverse and longitudinal momenta and hyperon species. We are now the beneficiaries of greatly improved knowledge about both quark and gluon distributions in hadrons, for example thanks to precise neutrino deep inelastic scattering studies at Fermilab and elswhere [19], and are looking forward to reliable error estimates for these functions. Although the Superconducting Supercollider (SSC) did not survive funding cuts, the Large Hadron Collider (LHC) is on track toward operation during the middle of this decade. New experiments have solved some mysteries of quarkonium production and hyperon polarization, but uncovered others.

During the Tevatron era the attitude of many physicists toward the "unexpected" may have become less flexible. In 1983 the possibilities for new physics seemed richer and less universally agreed upon than they do today. Searches were under way for magnetic monopoles, neutral heavy leptons, toponium, quark and lepton compositeness, and even an elusive bump at 1.8 MeV in the e^+e^- spectrum. Today, although some of these searches have even been pursued recently, many physicists seem apologetic if they are not looking for the odds-on favorite among most theorists, supersymmetry. The field thus seems somewhat more monolithic than it was in 1983. Part of the great advantage of the Tevatron was the opportunity it provided for a rich variety of experiments on a scale that could be managed by collaborations with modest resources but original ideas. One hopes to see future possibilities for this variety of approaches.

Roughly 45 fixed-target experiments were performed using the Tevatron during the period 1983–2000. These are summarized in Table 2; more details may be found in Ref. [20]. We shall touch upon some aspects of this program from the theoretical standpoint.

We describe progress on electroweak symmetry and neutrinos in Section 2, and on weak quark couplings in Section 3. Section 4 is devoted to charmed particle lifetimes, while Section 5 treats charm mixing and CP violation. Section 6 deals with other results on heavy quarks. Two topics in hadron structure, the magnetic moments of baryons and the polarization of hyperons, are reviewed in Sections 7 and 8. Some possibilities for unexpected physics are mentioned in Section 9, while Section 10 concludes.

II ELECTROWEAK SYMMETRY AND NEUTRINOS

A Precise measurements

The ratio R_ν of the rate of neutral-current to charged-current interactions of neutrinos was one of the first sources of information about the weak mixing angle θ_W, defined in lowest electroweak order as $\sin^2\theta_W \equiv 1-(M_W/M_Z)^2$. This relation has continued to define θ_W in the presence of electroweak radiative corrections, while a slightly different quantity $\theta_{\rm eff}$ is measured through precise studies of Z

TABLE 2. Fixed-target experiments at the Fermilab Tevatron, 1983–2000.

Topic	Subtopic	Fermilab expt. no.
Kaons	CP violation	621, 731, 773, 832
	Rare decays	799 (+ hyperons)
Hyperons	$\Sigma^- \to ne^-\bar{\nu}_e$	715
	$\mu(\Omega^-)$	756, 800
	Radiative decays	761
	Charmed baryons	781
	CP violation	871
Neutrinos	Counter	733, 744, 770, 815, 872
	Bubble chamber	632, 745
Hadron structure	Muon scattering	665, 782
	Direct photons	706
	Hadron jets	557/672, 609, 683
	Polarized scattering	581/704
	Structure functions	866
Pair spectrometers	Dimuons	605, 615, 772
	Dihadrons	605, 711, 789
Heavy quark production	Charm(onium)	400, 653, 687, 690, 705, 743, 769, 791, 831
	Beauty	690, 771, 789
Particle search	1.8 MeV/c^2 e^+e^- bump	774

couplings at LEP and SLC. Small differences between the two arise as a result of loops involving, for example, the top quark and the Higgs boson.

From a simplistic viewpoint, which is a slight distortion of the actual situation, the neutral-current cross section $\sigma_{NC}(\nu N)$ involves Z exchange, and the Z boson's mass is well measured, while the charged-current cross section $\sigma_{CC}(\nu N)$ involves exchange of the W, whose mass is less well measured. Thus, measurement of R_ν serves mainly to constrain M_W, whatever the mass of the top quark or Higgs boson. A similar conclusion applies to a combination of neutral-current and charged-current cross sections known as the Paschos-Wolfenstein [21] ratio,

$$R_{PW} \equiv \frac{\sigma_{NC}(\nu N) - \sigma_{NC}(\bar{\nu} N)}{\sigma_{CC}(\nu N) - \sigma_{CC}(\bar{\nu} N)} \quad . \tag{1}$$

The NuTeV Collaboration [22] has used this ratio to determine $M_W = 80.26 \pm 0.11$ GeV (for nominal $m_t,\ M_H$). Given the known value of the top quark mass [23], $m_t = 174.3 \pm 5.1$ GeV, this value of the W mass can be combined with other direct

measurements to constrain the Higgs boson mass M_H to lie below about 200 GeV.

B The tau neutrino

The tau neutrino is the one fermion in the Standard Model that remains to be observed directly. Confirmation would not only cement our confidence in the many indirect measurements that require its existence, but also would help us learn how to see ν_τ's in experiments which seek to study their appearance in oscillations.

A number of years ago a beam dump experiment was proposed [24] in order to produce and study ν_τ's. Cost and schedule constraints prevented its implementation. The main source of ν_τ's was expected to be the decay $D_s^+ \to \tau^+ \nu_\tau$. Since then, the D_s decay constant has been measured by several groups including one at Fermilab [25], with the most precise value [26] implying a favorable branching ratio for this process of about 6%. As of June 2000 the DONUT experiment (Fermilab E-872) had several ν_τ candidates, for which results now have been published [2].

C Neutrino oscillations

The evidence that neutrinos have mass and undergo oscillations from one species to another includes several results:

- Neutrinos from the Sun appear at the Earth with a probability ranging from about 30 to 60% of that expected, depending on their energies [27]. The interpretation of this effect in terms of neutrino oscillations [28] allows for several ranges of mass differences and mixing angles.
- Muon neutrinos produced in the atmosphere appear to oscillate into another species, most likely ν_τ, with near-maximal mixing $\sin^2 2\theta \simeq 1$ and $\Delta m^2 \simeq 3 \times 10^{-3}$ eV^2 [29].
- One experiment [30] has presented evidence for the oscillation $\bar{\nu}_\mu \to \bar{\nu}_e$, with an allowed region in $\sin^2 2\theta - \Delta m^2$ resembling a sinking canoe.

The confirmation and elaboration of the second and third of these results is an important part of Fermilab's future fixed-target program [31,32].

III WEAK QUARK COUPLINGS

The pattern of charge-changing couplings of the weak quarks is as much a fundamental mystery as the masses of the quarks, and probably springs from the same physics. It is expressed in terms of the unitary Cabibbo-Kobayashi-Maskawa (CKM) [6,12] matrix V, which has four real parameters for three families of quarks. These may be taken to be [4] (1) $\lambda = \sin\theta_C \simeq 0.22$, where θ_C is the Cabibbo angle [6,33]; (2) $A = |V_{cb}|/\lambda^2 \simeq 0.8$; (3) $\rho = \mathrm{Re}(V_{ub}/A\lambda^3) \simeq 0.0 - 0.3$; (4)

$\eta = -\mathrm{Im}(V_{ub}/A\lambda^3) \simeq 0.3 - 0.5$. The existence of a nonzero complex phase in some elements of V was a crucial ingredient in Kobayashi and Maskawa's explanation of CP violation in the neutral kaon system. It required the existence of the third quark family, both of whose members were discovered at Fermilab [34,35]. With only two families of quarks, a single parameter λ would have sufficed to describe the mixing [6,36].

Fermilab has played a major role in measuring elements of the CKM matrix, either directly or via loop effects. Neutrino and charm experiments confirm the expectations of a unitary V by showing that $|V_{cs}| \simeq 1$, $|V_{cd}| \simeq |V_{us}| \simeq 0.22$ [15,19]. Collider results on B meson and top quark decays have improved our information on V_{cb} and confirm (within wide limits) that $V_{tb} \simeq 1$ as expected from unitarity. Hyperon (Σ^-, Λ, $\Xi^0, \ldots$) beta decays [14,37] confirm that $|V_{us}| \simeq 0.22$ and provide insights into the nature of SU(3) violations [38] in these processes. Studies of CP-violating K^0–$\bar{K}^0$ mixing [16] and collider experiments on B^0–$\bar{B}^0$ mixing give information on the phase and magnitude of V_{td}, while future collider experiments on B_s–$\bar{B}_s$ mixing will constrain the ratio $|V_{ts}/V_{td}|$ and hence $|V_{td}|$, given our expectation that $V_{ts} \simeq -V_{cb}$.

A more extensive discussion of the constraints on V may be found in Refs. [13] and [39]. Here we mention only a few key points.

A Direct CP violation in neutral kaon decays to two pions

As noted in the Introduction, the definitive observation at Fermilab of direct CP violation in neutral kaon decays [16] has qualitatively validated the Kobayashi-Maskawa theory [12], which was previously favored over the superweak [11] picture just on the basis of the magnitudes of CKM matrix elements [39]. My own average (June 2000) for the parameter $\mathrm{Re}(\epsilon'/\epsilon)$ describing this effect, based on experiments at Fermilab and CERN [16,17,40,41] is $(19.2 \pm 4.6) \times 10^{-4}$, where I have included a scale factor to account for the poor agreement among these very challenging measurements. More data are expected from both Fermilab and CERN. The present world average is somewhat above the favored range of theoretical predictions [42], but uncertainties in hadronic matrix elements can probably account for any discrepancy [43].

B $K^+ \to \pi^+ \nu \bar{\nu}$

The decay $K^+ \to \pi^+ \nu \bar{\nu}$ is sensitive mainly to the top quark's contribution to a loop diagram, with a small correction for charm, and so constrains the combination $|1.4 - \rho - i\eta|$. One predicts [44] a branching ratio

$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \simeq 10^{-10} \left| \frac{1.4 - \rho - i\eta}{1.4} \right|^2 \quad , \tag{2}$$

so that for $0 \leq \rho \leq 0.3$ one expects a branching ratio $\mathcal{B} \simeq (0.8 \pm 0.2) \times 10^{-10}$, with additional errors associated with the charmed quark mass and the Wolfenstein parameter A. A measurement of this branching ratio to 10% could provide a significant constraint on the parameter ρ or could exhibit interesting deviations from the Standard Model prediction. At present one event has been recorded by Brookhaven Experiment E787 [45], corresponding to $\mathcal{B} = (1.5^{+3.4}_{-1.2}) \times 10^{-10}$. More data are expected, both from further analysis of E787 and from an approved follow-up experiment (E949) at Brookhaven [46]. A Fermilab proposal [47] also seeks to study this process.

C $K_L \to \pi^0 \ell^+ \ell^-$

The decay $K_L \to \pi^0 \ell^+ \ell^-$ has important CP-violating contributions, both direct (proportional to η) and indirect (resulting from the admixture ϵK_1 of the CP-even state in K_L). Each contribution separately would give rise to a branching ratio $\mathcal{B}(K_L \to \pi^0 e^+ e^-)$ of several parts in 10^{12}. Background from the decay $K_L \to \gamma \ell^+ \ell^-$ in which a final lepton radiates an extra photon [48] may limit the search for this process. Moreover, the CP-conserving process $K_L \to \pi^0 \gamma\gamma \to \pi^0 \ell^+ \ell^-$ also probably plays a role at a significant level. Present 90% c.l. upper limits [49] are $\mathcal{B}(K_L \to \pi^0 [e^+ e^-,\ \mu^+ \mu^-]) = [5.1, 3.8] \times 10^{-10}$, a factor of about 100 above interesting levels unless the indirect contribution is far greater than most estimates [44,50].

D $K_L \to \pi^0 \nu \bar{\nu}$

The decay $K_L \to \pi^0 \nu \bar{\nu}$ is purely CP-violating and provides a clean probe of η. The predicted branching ratio, proportional to $A^4 \eta^2$, is expected to be about 3×10^{-11} [44]. The best upper limit on the branching ratio utilizes the Dalitz decay of the π^0 and is 5.9×10^{-7} [49]. Proposals exist to improve these limits at Brookhaven [51] and Fermilab [52].

E Other rare kaon decays

A recent study of the decay $K_L \to \mu^+ \mu^- \gamma$ [53] may help us to learn more about the CKM matrix (particularly the parameter ρ) by pinning down long-distance effects due to the two-photon contribution in $K_L \to \gamma\gamma \to \mu^+ \mu^-$. Although it is not relevant to CKM physics, one should also mention the observation, both at Fermilab [54] and at CERN [55], of a CP- and/or T-violating asymmetry in the decay $K_L \to \pi^+ \pi^- e^+ e^-$, in accord with theoretical predictions [56] based on the observed CP-violating mixing in the neutral kaon system.

IV CHARM LIFETIMES

The lifetimes of charmed particles exhibit an interesting interplay of short-distance and long-distance effects, intermediate between the case of kaons, where long-distance effects dominate, and particles containing b quarks, where short-distance physics can explain most (but not all) of the pattern. Several effects must be taken into account.

1. The rate for the decay of a free charmed quark, $c \to s + (u\bar{d}, e\nu, \mu\nu)$ is given in terms of the muon decay rate $\Gamma_\mu = 4.55 \times 10^5$ s^{-1} by
$$\Gamma(c \to s + \ldots) \simeq 5 \left(\frac{m_c}{m_\mu}\right)^5 \Gamma_\mu \Phi \quad , \tag{3}$$
where the phase space correction Φ is approximately (0.45,0.97) for $m_c = 1.5$ GeV and $m_s = (0.5, 0.1)$ GeV, leading to a predicted lifetime $\tau(c) = (1.7, 0.8)$ ps. This is already in the ballpark of the longest charmed particle lifetime, that of the D^+ (see below).
2. A modest QCD enhancement of the subprocess $c \to su\bar{d}$ is expected in the channel in which s and u form a color antitriplet [9].
3. Final states with two or more identical quarks can be subject to either destructive or constructive "Pauli interference" [57].
4. Long-distance (e.g., resonant) effects can enhance "non-exotic" channels, as they appear to do in the dominance of $\Delta I = 1/2$ weak nonleptonic decays of kaons and hyperons [8]. Thus, for example, the lifetime of K_S, 0.089 ns, is much shorter than that (12 ns) of the K^+. The K_S can decay to $\pi\pi$ in an $I = 0$ channel, for which the $\pi\pi$ interaction is strong (if not exactly resonant). By contrast, $K^+ \to \pi^+\pi^0$ must be purely $I = 2$, and there are no known resonances with $I = 2$.

The Tevatron has been a major player in establishing the interesting hierarchy of charmed particle lifetimes displayed in Table 3. Evidence for all of the above mechanisms seems to be present. The key to these studies has been the isolation of charmed particles in the presence of formidable backgrounds by detecting their decays, only fractions of a millimeter from their production, using silicon vertex detectors.

V CHARM MIXING AND CP VIOLATION

A D^0–$\bar{D}^0$ mixing and lifetime difference

Both at Fermilab and elsewhere, there are new and potentially exciting results on the D^0–$\bar{D}^0$ system. The CLEO Collaboration [59] has studied the time-dependence

TABLE 3. Charmed particle lifetimes and effects contributing to them.

Particle	Lifetime (ps) [58]	Comments
D^+	1.051 ± 0.013	Exotic channel; Pauli int. lowers Γ
D^0	0.4126 ± 0.0028	Rate QCD-enhanced
D_s^+	$0.496^{+0.010}_{-0.009}$	Rate QCD-enhanced (suppr. by binding?)
Λ_c^+	0.206 ± 0.012	Subprocess $cd \to su$ effective
Ξ_c^0	$0.098^{+0.023}_{-0.015}$	Subprocess $cd \to su$ effective;
		Pauli int. raises Γ
Ξ_c^+	$0.33^{+0.06}_{-0.04}$	No subprocess $cd \to su$;
		Pauli int. raises Γ
Ω_c^0	0.064 ± 0.020	Pauli int. raises Γ

of "wrong-sign" decays $D^0 \to K^+\pi^-$, thereby learning a combination of parameters describing the mass difference Δm and width difference $\Delta\Gamma$ between the CP-even and CP-odd combinations of D^0 and $\bar{D}^0$. If one defines Γ as the average width of these two states, $x \equiv \Delta m/\Gamma$, $y \equiv \Delta\Gamma/\Gamma$, and δ to be a relative final-state phase between $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^+\pi^-$, the CLEO result entails

$$-5.8\% < y' \equiv y\cos\delta - x\sin\delta < 1\% \quad , \tag{4}$$

hinting (though not with sufficient significance) at a negative value of y'.

More recently, the FOCUS Collaboration (Fermilab E831) [60] has directly compared the lifetime of D^0 in the $K^-\pi^+$ mode, which is half CP-even and half CP-odd, with that in the K^+K^- mode, which is purely CP-even, finding

$$y = (3.42 \pm 1.39 \pm 0.74)\% \quad . \tag{5}$$

Although the deviation from zero is not yet statistically compelling, the central value is far larger than theoretical predictions [61] and, if confirmed, could be a hint of new physics.

B CP violation

CP-violating asymmetries in charmed meson decays are expected to be small in the Standard Model. Two factors contribute to the expected smallness of penguin $c \to u$ amplitudes and D^0–$\bar{D}^0$ mixing. First, the internal d and s quark contributions nearly cancel one another, as entailed in the original Glashow-Iliopoulos-Maiani (GIM) mechanism [62]. Second, the largest internal quark mass in the loop diagram for $c \to u$ is m_b, which is much smaller than that (m_t) in the loop diagrams for $s \to d$ or $b \to (d, s)$ transitions. If we define

$$\mathcal{A}_{\rm CP} \equiv \frac{\Gamma(D) - \Gamma(\bar{D})}{\Gamma(D) + \Gamma(\bar{D})} \quad , \tag{6}$$

the FOCUS Collaboration [63] finds

$$\begin{aligned}
\mathcal{A}(D^+ \to K^- K^+ \pi^+) &= -0.006 \pm 0.011 \pm 0.005 \quad , \\
\mathcal{A}(D^0 \to K^- K^+) &= -0.001 \pm 0.022 \pm 0.015 \quad , \\
\mathcal{A}(D^0 \to \pi^+ \pi^-) &= 0.048 \pm 0.039 \pm 0.025 \quad .
\end{aligned} \tag{7}$$

All these values are consistent with zero at the several percent level and represent an improvement over previous bounds.

VI HEAVY QUARK RESULTS

A Υ production

The E605 Collaboration has studied the relative production in hadronic reactions of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ [64]. The relatively large height of the 3S peak leaves at least some role for an electromagnetic cascade from the 3P states, which are expected to lie below $B\bar{B}$ threshold [65].

B J/ψ and ψ' production

The production cross section of the J/ψ in hadronic interactions [66] is too large to be accounted for purely by electromagnetic cascades from the χ_c states [8,67] or by direct production of the color-singlet $c\bar{c}$ state. A gluonic component of the wave function, involving a color-octet $c\bar{c}$ state, seems to be required [68]. This should not be so surprising in view of the fact that roughly half the nucleon's momentum is carried by gluons. Difficulties still exist in explaining the production of the 2S $c\bar{c}$ state, the ψ'. (For a recent optimistic discussion see Ref. [69].) Is this because the 2S state has light quarks in its wave function as a result of proximity to $D\bar{D}$ threshold? Some problems must remain for the next generation of particle physicists!

C b quark production

Many experiments at the Tevatron (e.g., [70,71]) searched for the production of b quarks by 800 GeV protons on a fixed target. The cross section is relevant for CP-violation studies now under way at similar energies at HERA-b. Using J/ψ's identified as B decay products by their displaced vertices, for example, the E789 Collaboration [72] has measured $\sigma(pN \to b\bar{b} + X) = 5.7 \pm 1.5 \pm 1.3$ nb/nucleon. This value, while small, is larger than the $e^+e^- \to b\bar{b}$ cross section at the $\Upsilon(4S)$.

VII BARYON MAGNETIC MOMENTS

Several experiments at Fermilab have added to our knowledge about hadron structure through the measurement of baryon magnetic moments [73]. The naïve quark model predicts that for a baryon composed of two quarks q_1 of one kind and one q_2 of another, the magnetic moment will be [74]

$$\mu(q_1 q_1 q_2) = \frac{4}{3}\mu(q_1) - \frac{1}{3}\mu(q_2) \quad . \tag{8}$$

This prediction assumes that all quarks in the baryon are in a relative S-wave. A simple argument based on Fermi statistics and color then demands that the two identical quarks q_1 be in a state of spin 1, and the coefficients in the above equation are related to the Clebsch-Gordan coefficients for coupling this system with the spin of q_2 to obtain total spin of 1/2.

If the ground-state baryon contains configuration-mixed states [75], one can still obtain some predictions [76]. The proton and neutron mix differently with higher states than the Σ and Ξ since decuplets of SU(3) contain states which can mix with the latter but not with the former. Thus, one writes

$$\begin{aligned} \mu(q_1 q_1 q_2) &= (A-B)\mu(q_1) + B\mu(q_2) \quad (p,n) \quad , \\ \mu(q_1 q_1 q_2) &= (A'-B')\mu(q_1) + B'\mu(q_2) \quad (\Sigma,\Xi) \quad . \end{aligned} \tag{9}$$

The assumption that the total orbital angular momentum of quarks in a baryon vanishes entails the relation $A = A' = 1$ [76].

The predictions of the naïve [74] and configuration-mixed [76] models are compared with experimental values [58] in Table 4. The configuration-mixed model was to be judged on the basis of its prediction of a more negative Ω^- magnetic moment than the naïve model's prediction $\mu(\Omega^-) = 3\mu(s) = 3\mu(\Lambda)$. The experimental value is almost exactly between the two predictions – if anything, closer to the naïve number.

The configuration-mixed model of Ref. [76] was probably an oversimplification. Deep inelastic scattering experiments tell us that some of the proton's spin is carried by gluons or orbital angular momentum and by sea quarks, so it is remarkable that the naïve model works as well as it does.

The study of hyperon magnetic moments at Fermilab builds upon a systematic investigation of hyperon polarizations, whose pattern is still a puzzle for theorists. We now discuss these results briefly.

VIII HYPERON POLARIZATION

A recent Tevatron fixed-target experiment on hyperon polarization, from which earlier references may be traced, is Experiment 761 [77]. We refer the reader to the original articles for illustrations of the behavior of polarizations as functions

TABLE 4. Baryon magnetic moments (in nuclear magnetons) in naïve and configuration-mixed quark models, compared with experimental values.

Baryon	Naïve	Mixed	Experiment
p	Input	Input	2.793
n	Input	Input	-1.913
Λ	Input	> -0.75	-0.613 ± 0.004
Σ^+	2.67	2.48 ± 0.02	2.458 ± 0.010
$\Sigma^0 \to \Lambda$	-1.63	> -1.78	-1.61 ± 0.08
Σ^-	-1.09	Input	-1.160 ± 0.025
Ξ^0	-1.44	Input	-1.250 ± 0.014
Ξ^-	-0.50	Input	-0.6507 ± 0.0025
Ω^-	-1.84	-2.26 ± 0.09	-2.02 ± 0.05

of Feynman x_f and transverse momentum P_t, and merely describe the pattern. If the net spin of a hyperon is parallel to that of the strange quark(s), as in the case of the Λ, Ξ^0, and Ξ^-, the polarization is negative. If, on the other hand, the net spin is antiparallel to that of the strange quark, as in the case of the Σ^+, the polarization is positive. This behavior was understood qualitatively twenty years ago in a fragmentation model by DeGrand and Miettinen [78]. However, the polarization of *antihyperons* was not predicted in this model, and the pattern so far has resisted explanation. For example, the $\bar{\Sigma}^-$ is produced with positive polarization, about half that of its antiparticle, the Σ^+! The $\bar{\Xi}^+$ is produced with approximately the same polarization as the Ξ^- [79]! Prediction of the pattern is another puzzle for future generations.

IX THE UNEXPECTED

The definition of "unexpected" depends on one's theoretical predilections; it is the variety of these which leads to surprises. I give just two examples.

A Neutral heavy leptons

Right-handed neutrinos are natural in many schemes such as SO(10) and its subgroup SO(6) $\otimes$ SO(4) which seek to unify the electroweak and strong interactions. Large Majorana masses M of right-handed neutrinos don't violate any known symmetry, and the lepton number violation which they entail is one candidate [80] for the origin of the net baryon number of the Universe.

It appears that neutrinos have tiny masses, possibly smaller than 0.1 eV on the basis of atmospheric ν_μ oscillations suggested by experiments at SuperKamiokande

[29]. The seesaw model of these masses [81] $m_\nu = m^2_{\rm Dirac}/M$ then implies that right-handed neutrino masses M must be above the reach of conventional accelerator experiments, but it is wise to search anyway. The NuTeV Collaboration [82] has extended previous experimental limits on masses and mixings of right-handed neutrinos produced, for example, in decays of kaons and charmed particles, and has placed limits [83] on the production of a 33.6 MeV neutral lepton suggested by another experiment [84]. Recently NuTeV has reported three intriguing dimuon events from this search whose rate appears to exceed background estimates [85]. For one interpretation, see Ref. [86].

B Unconventional families

The repetitive family structure of the quarks and leptons is reminiscent of the beginning of the periodic table of the elements. Does it suggest a composite structure for these objects? Are new symmetries involved? As in the case of the periodic table, it may be necessary to see variations in the pattern before its origin becomes clear. Unification schemes based on groups beyond SO(10), such as E_6 [87], predict such variations, entailing isosinglet quarks of charge $-1/3$, vector-like (left-right symmetric) lepton multiplets, and "sterile" (weak isosinglet) neutrinos which need not have large Majorana masses.

The LSND claim [30] for $\bar\nu_\mu \to \bar\nu_e$ oscillations, when combined with evidence for solar and atmospheric neutrino oscillations, probably requires at least one sterile neutrino. The large hierarchy between the b and t masses could indicate that mixing between the b and a heavier quark of charge $-1/3$ is depressing the b mass [88]. We look forward to future neutrino oscillation experiments at Fermilab [31,32] and elsewhere to elucidate the pattern of neutrino masses and mixings, and to searches at high-energy colliders which may uncover new states of matter.

X CONCLUSIONS

The Fermilab Tevatron's fixed-target program has provided a superb variety and scope of experiments for nearly 20 years. It has addressed many issues through precision measurements, as is natural for a facility working at the frontier of luminosity rather than the highest center-of-mass energy. Now we are entering an era of even more precise and even lower-energy fixed target physics at Fermilab, to be provided by the Main Injector. We can look forward to exciting physics from this program, in such areas as rare kaon decays, neutrino oscillations, and – we hope – a generous dose of searches for the unexpected.

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